Tracking Particles In Accelerator Optics With Crystal Elements

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Abstract. Bent channeling crystals as elements of accelerator optics with extreme, 1000-Tesla intracrystalline fields can find many applications in accelerator world from TeV down to MeV energies. Situated in accelerator ring, they serve for beam scraping or extraction, e.g. in RHIC and IHEP U70. Crystal itself is a miniature beamline with its own "strong focusing", beam loss mechanisms etc. We describe the algorithms implemented in the computer code CATCH used for simulation of particle channeling through crystal lattices and report the results of tracking with 100-GeV/u Au ions in RHIC and with 70-GeV and 1-GeV protons in U70. Recent success of IHEP where a tiny, 2-mm Si crystal has channeled a 10^{12} p/s beam of 70-GeV protons out of the ring with efficiency 85% followed the prediction of computer model.

1 Introduction

The idea to deflect proton beams using bent crystals, originally proposed by E.Tsyganov [1], was demonstrated in 1979 in Dubna on proton beams of a few GeV energy. The physics related to channneling mechanisms was studied in details, in the early 1980's, at St.Petersburg, in Dubna, at CERN, and at FNAL using proton beams of 1 to 800 GeV (see refs., e.g. in [2]). Recently, the range of bent crystal channeling was expanded down to MeV energy[3], now covering 6 decades of energy.

Crystal-assisted extraction from accelerator was demonstrated for the first time in 1984 in Dubna at 4-8 GeV and deeply tested at IHEP in Protvino starting from 1989 by exposing a silicon crystal bent by 85 mrad to the 70 GeV proton beam of U-70. The Protvino experiment eventually pioneered the first regular application of crystals for beam extraction: the Si crystal, originally installed in the vacuum chamber of U-70, served without replacement *over 10 years*, delivering beam for particle physicists all this time. However its channeling efficiency was never exceeding a fraction of %.

In the 1990's an important milestone was obtained at the CERN SPS. Protons diffusing from a 120 GeV beam were extracted at an angle of 8.5 mrad with a bent silicon crystal. Efficiencies of $\sim$10%, orders of magnitude higher than the values achieved previously, were measured for the first time [4]. The extraction studies at SPS clarified several aspects of the technique. In addition, the extraction results were found in fair agreement with Monte Carlo predictions [2]. In the late 1990's another success came from the Tevatron extraction experiment where a crystal was channeling a 900-GeV proton beam with an efficiency of ~30% [5]. During the FNAL test, the halo created by beam-beam interaction in the periphery of the circulating beam was extracted from the beam pipe without unduly affecting the backgrounds at the collider detectors.

Possible application of crystal channeling in modern hadron accelerators, like slow extraction and halo collimation, can be exploited in a broad range of energies, from sub-GeV cases (i.e. for medical accelerators) to multi-TeV machines (for high-energy research).

Crystal collimation is being experimentally studied at RHIC with gold ions and polarized protons of 100-250 GeV/u [6] and has been proposed and studied in simulations for the Tevatron (1000 GeV) [7], whilst crystal-assisted slow extraction is considered for AGS (25 GeV protons) [8]. In all cases, the critical issue is the channeling efficiency.

2 Crystal as a beamline

Let us understand how the crystal symmetry may be used for steering a particle beam. Any particle traversing an amorphous matter or a disaligned crystal experiences a number of uncorrelated collisions with single atoms. As these encounters may occur with any impact parameters, small or large ones, a variety of processes take place in the collision events. In disordered matter one may consider just a single collision, then simply make a correction for the matter density.

The first realization that the atomic order in crystals may be important for these processes dates back to 1912[9]. In early 1960s the channeling effect was discovered in computer simulations and experiments which observed abnormally large ranges of ions in crystals[10]. The orientational effects for charged particles traversing crystals were found for a number of processes requiring a small impact parameter in a particle–atom collision.

The theoretical explanation of the channeling effects has been given by Lindhard [11], who has shown that when a charged particle has a small incident angle with respect to the crystallographic axis (or plane) the successive collisions of the particle with the lattice atoms are correlated, and hence one has to consider the interaction of the charged particle with the atomic string (plane). In the low-angle approximation one may replace the potentials of the single atoms with an averaged *continuous potential.* If a particle is misaligned with respect to the atomic strings but moves at a small angle with respect to the crystallographic plane, one may take advantage of the continuous potential for the atomic plane, where averaging is made over the two planar coordinates:

$$U_{\mathrm{pl}}(x) = N d_{\mathrm{p}} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} V(x, y, z) \mathrm{d}y \mathrm{d}z \qquad (1)$$

where $V(x, y, z)$ is the potential of a particle–atom interaction, N is the volume density of atoms, d_p is the interplanar spacing.

The atomic plane (string) gently steers a particle away from the atoms, thus suppressing the encounters with small impact parameters. The transverse motion of a particle incident at some small angle with respect to one of the crystal axes or planes is governed by the continuous potential of the crystal lattice. The fields of the atomic axes and planes form the potential wells, where the particle may be trapped. In this case one speaks of *channeling* of the particle: an *axial channeling* if the particle is bound with atomic strings, and a *planar channeling* if it is bound with atomic planes.

The interaction of the channeled particle with a medium is very different from a particle interaction with an amorphous solid. For instance, a channeled proton moves between two atomic planes (layers) and hence does not collide with nuclei; moreover, it moves in a medium of electrons with reduced density. In the channeling mode a particle may traverse many centimeters of crystal (in the ~100 GeV range of energy).

Leaving aside the details of channeling physics, it may be interesting to mention that accelerator physicist will find many familiar things there:

- Channeled particle oscillates in a transverse nonlinear field of a crystal channel, which is the same thing as the "*betatronic oscillations*" in accelerator, but on a much different scale (the wavelength is 0.1 mm at 1 TeV in silicon crystal). The analog of "beta function" is order of 10 μm in crystal. The number of oscillations per crystal length can be several thousand in practice. The concepts of beam emittance, or particle action have analogs in crystal channeling.
- The crystal nuclei arranged in crystallographic planes represent the "*vacuum chamber walls*". Any particle approached the nuclei is rapidly lost from channeling state. Notice a different scale again: the "vacuum chamber" size is ~2 Å.
- The well-channeled particles are confined far from nuclei (from "aperture"). They are lost then only due to scattering on electrons. This is analog to "*scattering on residual gas*". This may result in a gradual increase of the particle amplitude or just a catastrophic loss in a single scattering event.
- Like the real accelerator lattice may suffer from *errors of alignment*, the lattice of real crystal may have dislocations too, causing an extra diffusion of particle amplitude or (more likely) a catastrophic loss.
- Accelerators tend to use low temperature, superconducting magnets. Interestingly, the crystals cooled to *cryogenic temperatures* are more efficient, too.

In simulations, the static-lattice potential is modified to take into account the thermal vibrations of the lattice atoms. Bending of the crystal has no effect on this potential. However, it causes a centrifugal force in the non-inertial frame related to the atomic planes. To solve the equation of motion in the potential $U(x)$ of the bent crystal, as a first approximation to the transport of a particle,

$$pv\frac{d^2x}{dz^2} = -\frac{dU(x)}{dx} - \frac{pv}{R(z)}\,, \tag{2}$$

(x being the transversal, z the longitudinal coordinate, pv the particle longitudinal momentum and velocity product, $R(z)$ the local radius of curvature), we use the fast form of the Verlet algorithm:

$$x_{i+1} - x_i = (\theta_i + 0.5 f_i \delta z)\delta z\,, \tag{3}$$

$$\theta_{i+1} - \theta_i = 0.5(f_{i+1} + f_i)\delta z \tag{4}$$

with θ for dx/dz, f for the 'force', and δz for the step. It was chosen over the other second order algorithms for non-linear equations of motion, such as Euler-Cromer's and Beeman's, owing to the better conservation of the transverse energy shown in the potential motion.

Beam bending by a crystal is due to the trapping of some particles in the potential well $U(x)$, where they then follow the direction of the atomic planes. This simple picture is disturbed by scattering processes which could cause (as result of one or many acts) the trapped particle to come to a free state (feed out, or dechanneling process), and an initially free particle to be trapped in the channeled state (feed in, or volume capture).

Feed out is mostly due to scattering on electrons, because the channelled particles keep far from the nuclei. The fraction of the mean energy loss corresponding to single electronic collisions can be written as follows [12]:

$$-\frac{dE}{dz} = \frac{D}{2\beta^2}\rho_e(x)\ln\frac{T_{max}}{I}\,, \tag{5}$$

with $D = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\rho$, z for the charge of the incident particle (in units of e), ρ for the crystal density, Z and A for atomic number and weight, T_{max} the maximum energy transfer, and the other notation being standard [12]. It depends on the local density $\rho_e(x)$ (normalized on the amorphous one) of electrons. The angle of scattering in soft collisions can be computed as a random Gaussian with r.m.s. value $\theta^2_{rms} = \frac{m_e}{p^2}(\delta E)_{soft}$ where $(\delta E)_{soft}$ is the soft acts contribution. The probability of the hard collision (potentially causing immediate feed out) is computed at every step. The energy transfer T in such an act is generated according to the distribution function $P(T)$:

$$P(T) = \frac{D\rho_e(x)}{2\beta^2}\frac{1}{T^2}\,. \tag{6}$$

The transverse momentum transfer q is equal to $q = \sqrt{2m_eT + (T/c)^2}$. Its projections are used to modify the angles θ_x and θ_y of the particle.

The multiple Coulomb scattering on nuclei is computed by the approximation Kitagawa-Ohtsuki $\langle\theta^2_{sc}\rangle_{amorph}\cdot\rho_n(x)$, i.e. the mean angle of scattering squared is proportional to the local density of nuclei $\rho_n(x)$. The probability of nuclear collision, proportional to $\rho_n(x)$, is checked at every step.

3 Channeling of protons at IHEP Protvino

In crystal extraction, the circulating particles can cross several times the crystal without nuclear interactions. Unchanneled particles are deflected by multiple scattering and eventually have new chances of being channeled on later turns. The crystal size should be well matched to the beam energy to maximise the transmission efficiency. To clarify this mechanism an extraction experiment was started at IHEP Protvino at the end of 1997 [13].

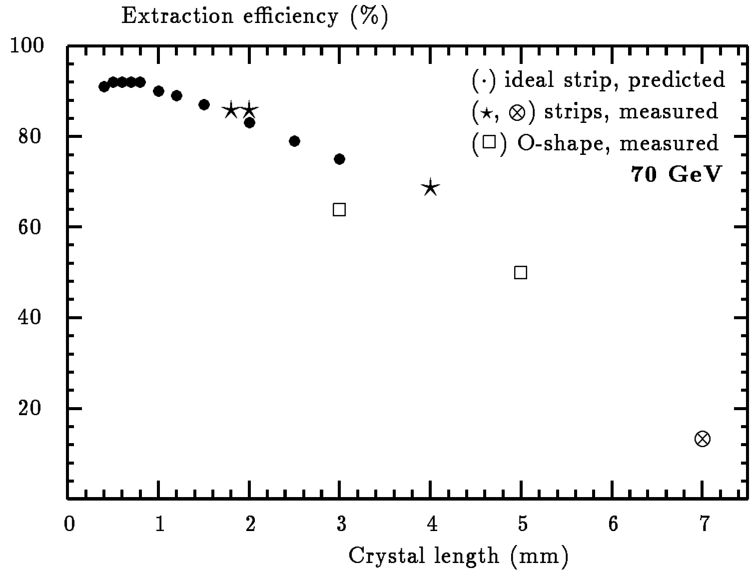

Fig. 1. Crystal extraction efficiency as measured for 70-GeV protons at IHEP (⋆, □, ⊗), and Monte Carlo prediction (o) for a perfect "strip" deflector.

As showed the simulation study of multi-turn crystal-asisted extraction taking into account the multiple encounters with crystal of the protons circulating in the ring, Fig.1, the crystal had to be quite miniature - just a few mm along the beam of 70 GeV protons - in order the extraction could benefit from crystal channeling.

Over the recent years, the experiment gradually approached the optimum found in the simulations. The recent extraction results, with 2 mm crystal of silicon, are rather close to the top of the theoretical curve. The experimentally demonstrated figure is excellent: 85% of all protons dumped onto the crystal were channeled and extracted out of the ring, in good accordance with prediction.

The channeling experiment was repeated with the same set-up at much different energy, 1.3 GeV. Here, no significant multiplicity of proton encounters with the crystal was expected due to strong scattering of particles in the same, 2-mm long crystal. The distribution of protons 20 m downstream of the crystal

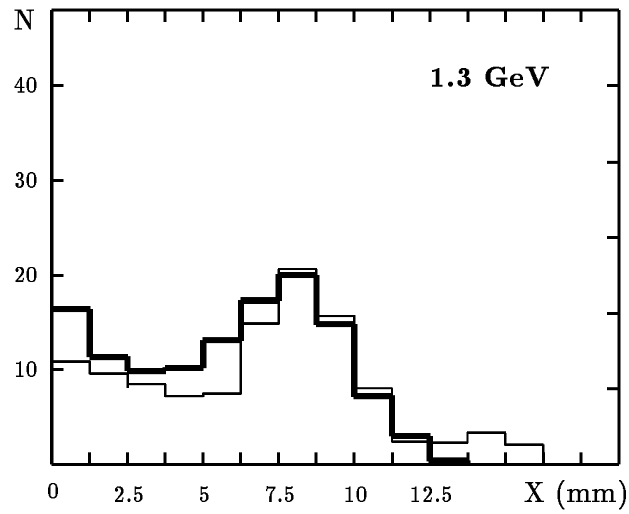

Fig. 2. The profile of 1.3 GeV protons on the collimator face as measured (thick line) and as predicted (thin) by simulations.

was observed on the face of a collimator, Fig.2. About half of the particles are found in the channeled peak. The distribution of 1.3 GeV protons is in good agreement with Monte Carlo predictions.

4 Channeling of gold ions at RHIC

In present day high energy colliders, the requirements of high luminosity and low backgrounds place strict requirements on the quality of the beams used. At facilities like RHIC, intra-beam scattering and other halo forming processes become a major concern[6]. Transverse beam growth not only leads to increased detector backgrounds, but also reduces dynamic aperture of the accelerator leading to particle losses at high beta locations. To minimize these effects, an efficient collimation system is needed.

The optics of two stage collimation systems have been reported numerous places[14]. The main disadvantage of the usual two stage system is that particles hitting the primary collimator with small impact parameters can scatter out of the material, causing a more diffuse halo. Using a bent crystal as the primary collimator in such a system, the channeled particles are placed into a well defined region of phase space. This allows the placement of a secondary collimator such that the impact parameters of the channeled particles are large enough to reduce the scattering probability, and most of the particles that hit the collimator are absorbed.

For the 2001 run, the yellow (counter-clockwise) ring had a two stage collimation system consisting of a 5 mm long crystal and a 450 mm long L-shaped copper scraper. Both are located in a warm section downstream of the IR triplet magnets in the 7 o'clock area.

The simulations of the collimation system included three major code components, UAL/TEAPOT for particle tracking around the accelerator [15], CATCH [16] to simulate particle interactions in the crystal, and the K2 [14] code to implement the proton scattering in the copper jaw. Gold ions and protons are tracked around the RHIC yellow ring, starting at the crystal. Particles that hit the crystal or the copper jaw are transfered to the proper program for simulation and then transfered back into TEAPOT to be tracked through the accelerator together with the noninteracting particles. In addition, the coordinates of each particle are saved at the entrance and exit of the crystal and scraper.

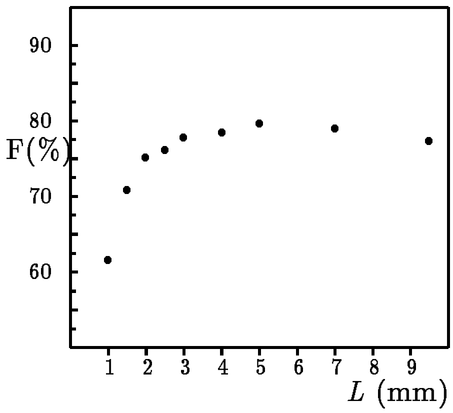

Fig. 3. Single-pass bending efficiency for 100-GeV/u Au ions vs crystal length, for 0.5 mrad bending.

The beam distribution at the entrance of the crystal was presented by the sample of fully stripped gold ions generated as described in [6]. We plot in Fig.3 how many particles were bent at least 0.1 mrad (this includes the particles channeled part of the crystal length as they are steered through the angles that might be sufficient for interception by the downstream collimator) when the incident particles are well within the acceptance of the crystal aligned to the beam envelope.

The gold ions tracked through the crystal and transported through the RHIC ring were eventually lost, at collimator and beyond. Fig.4 shows the losses around the RHIC rings from the particles scattered of the primary and secondary collimators and the losses from the particles deflected by the crystal. Two extreme cases are presented when the primary collimator downstream of the crystal is wide open and when it is set at 5 σ_x , the same horizontal distance as a front edge of the crystal.

The commissioning of the crystal collimator has occurred in the year 2001

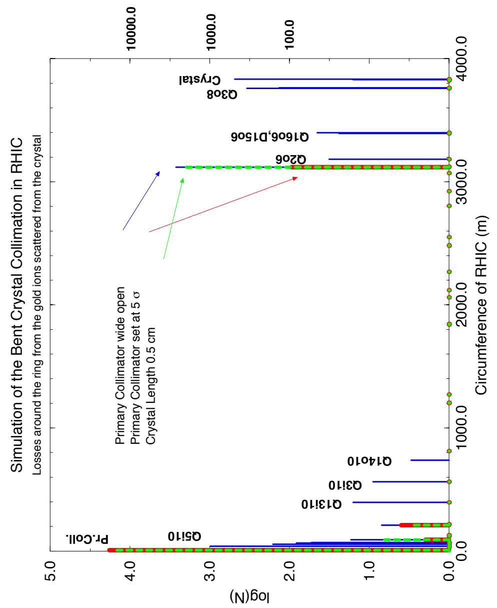

Fig. 4. Losses around the RHIC rings.

run. Once the efficiency of the crystal collimator has been determined, a second apparatus will be built for the blue ring. The collimator can be used in a variety of experiments to determine beam attributes such as size, angular profile, and diffusion rates. Experience gained at RHIC will be important for the plans to implement crystal extraction in the AGS [8] for a neutrino mass experiment.

5 Summary

The channeling crystal efficiency has reached unprecedented high values. The same 2 mm long crystal was used to channel 70 GeV protons with an efficiency of 85.3±2.8% and 1.3 GeV protons with an efficiency of 15-20%. The efficiency results well match the figures theoretically expected for ideal crystals. Theoretical analysis allows to plan for extraction and collimation with channeling efficiencies over 90-95%.

The high figures obtained in extraction and collimation provide a crucial support for the ideas to apply this technique in beam cleaning systems, for instance in RHIC and at the Tevatron. Earlier Tevatron scraping simulations [7] have shown that crystal scraper reduces accelerator-related background in CDF and D0 experiments by a factor of ~10.

Besides the experience gained in crystal extraction and collimation at IHEP Protvino, first experimental data is coming from RHIC where crystal collimator [6] has been commissioned. This technique is potentially applicable also in LHC for instance to improve the efficiency of the LHC cleaning system by embedding bent crystals in the primary collimators. This work is supported by INTAS-CERN grant 132-2000.

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